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ON GRAVITY MEASUREMENTS AT SEA

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THE OHIO STATE UNIVERSITY RESEARCH FOUNDATION

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The Ohio State University Research Foundation

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FOREWORD

This report was prepared by the Mapping and Charting Research Laboratory of the Ohio State University Research Foundation, under USAF Contract No. AF 18(600)90. The contract was administered under the direction of the Mapping and Charting Branch, Photographic Reconnaissance Laboratory, Air Research and Development Command, Wright-Patterson Air Force Base, Dayton, Ohio, with Mr. D.L. Radcliffe, Chief of the Mapping and Charting Branch, as Project Engineer.

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ABSTRACT

As the gravity measurements at sea are very important for establishing the World Geodetic System the author gives a glimpse of the history, theory and praxis of these measurements as well as of their reduction to sea level. The most important gravity measuring cruises will be listed. Some erroneous opinions concerning the speed and accuracy of the gravity measurements at sea will be corrected.

PUBLICATION REVIEW

The publication of this report does not constitute approval by the Air Force of the findings or conclusions contained therein. It is published only for the exchange and stimulation of ideas.

FOR THE COMMANDING GENERAL:

Richard W. Dillin

for GORDON A. BLAKE
Brigadier General, USAF
Chief, Weapons Components Division

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INTRODUCTION

The first, although primitive, instrument for gravity measurements at sea was the "Bathometer" of W. Siemens which he used in 1875, but without success.

The apparatus devised by Mohn in 1899 for determining the gravity correction of barometers is significant because in it the interesting boiling point thermometer has been used for the first time in estimating gravity. O. Hecker improved this method and used it in 1901-1909 in his three gravity measurement cruises to the Atlantic and Indian Oceans as well as to the Black Sea.

The principle of this method is as follows: the mercury column of a barometer maintains equilibrium with the pressure of the outside air. If the gravity will increase (or decrease) a little, under unchanged other conditions, not only the air pressure but the weight of the mercury column as well will increase (or decrease). Thus, the equilibrium prevails again so that no changes of gravity can be realized. The mercury column has therefore the same height at different values of gravity. As the boiling temperature of water depends on the air pressure we could obtain the absolute air pressure if we only were able to measure the boiling temperature. This we can do by the aid of boiling point thermometers. In comparing this absolute air pressure with the relative air pressure

obtained from the barometer the value of gravity can be determined.

Although this method is not capable of high accuracy the measurements by Hecker were able to prove that isostatic equilibrium prevails at the oceans.

In 1939 the German geophysicist H. Haalck used for gravity measurements at sea a gravimeter devised by him in 1931. The principle of this instrument is as follows: the pressure, p, of an enclosed gas can be measured by the height, h, of a mercury column of a barometer, because we have the equation

$$p = h \rho g$$

where ρ is the density of mercury and, g, the gravity.

In differentiating this equation logarithmically and using the equation of Boyle-Gay-Lussac we get

$$\frac{dp}{p} = -\frac{dv}{v} + \alpha \cdot dt = \frac{dh}{h} + \frac{d\rho}{\rho} + \frac{dg}{g}$$

where α is the expansion coefficient of the gas and dt the change of the temperature. If now dh/h can be measured with the relative accuracy of 10^{-6} and dt with the accuracy of $.0003^\circ$ C, the error of the measured, dg, is only 1 mgal.

The instrument of Haalck is satisfactory for gravity measurements on land. As to the gravity measurements at sea his test measuring trips to the Baltic Sea have not been promising.

Very interesting is the method which uses the gravimeter in a diving bell which is lowered to the bottom of the sea. This method

is possible in the shallow waters. It has also been used by the U.S. Geological Survey for the gravity measurements on the Continental Shelf off the Louisiana-Texas coast with remarkable success.

Still better is the underwater gravimeter of the Gulf Oil Co., because only the measuring instrument needs to be lowered to the bottom of the sea and the gravity can be recorded by means of the remote control apparatus on board of a ship. This method also has had success. The Gulf Oil Co. has carried out more than 1000 gravity measurements on the Continental Shelf of the Gulf of Mexico to a depth of 600 feet.

SECTION I

PENDULUM MEASUREMENTS AT SEA

1.1 The methods for the gravity measurements at sea, mentioned above either give a too low accuracy (boiling-point thermometer and Haalck's gravimeter) or can be used only in shallow waters (diving bell and underwater gravimeter). Therefore it is very good that one instrument or type of equipment exists which can give us gravity values with a sufficient accuracy in the open oceans. This is the pendulum apparatus of Vening Meinesz, which at least so far is the only successful instrument for this purpose. As, however, this method requires not only a great deal of time but also a submarine, a gravimeter which could be used in a surface boat would be enormously important. As such instrument does not exist at least by now I will explain briefly the principles of the Vening Meinesz pendulum apparatus.

1.2 The differential equation of a <u>free</u> swinging pendulum is

$$\frac{d^2\varphi}{dt^2} + \frac{g}{\ell}\sin\varphi = 0$$

where φ is the phase angle of the pendulum and ℓ, the "mathematical" length of it. As φ is always very small, we can write φ instead of $\sin\varphi$ so that we get

$$\frac{d^2\varphi}{dt^2} + \frac{g}{\ell}\varphi = 0$$

This equation presumes, however, that the pendulum is in fact "free". This is true only, if the suspension point is absolutely stable, which is very seldom the case. Even if we use low concrete pillars as base for the pendulum apparatus, the pillar and with it the suspension edge of the pendulum apparatus begin to sway.

1.3 In this case the pendulum is no more free, and its equation is

$$\frac{d^2\varphi}{dt^2} + \frac{g}{\ell}\varphi + \frac{a}{\ell} = 0$$

where, a, is the horizontal acceleration of the edge of the pendulum in the swinging plane of it. The sway brings about difficulties which are already found in the gravity measurements on dry land. At sea it is so dangerous that no gravity measurements from the surface boats can be carried out. Even in the submarines one has to use a special type of pendulum apparatus.

1.4 Vening Meinesz uses two pendulums of equal length which are swinging in the <u>same plane</u> and in opposite directions, with the phase difference 180°.

1.5 Supposing that the lengths of two pendulums are ℓ_1 and ℓ_2, and the phase angles are φ_1 and φ_2, we get the equations:

$$\begin{cases} \dfrac{d^2\varphi_1}{dt^2} + \dfrac{g}{\ell_1}\varphi_1 + \dfrac{a}{\ell_1} = 0 \\ \dfrac{d^2\varphi_2}{dt^2} + \dfrac{g}{\ell_2}\varphi_2 + \dfrac{a}{\ell_2} = 0 \end{cases}$$

If now $\ell_1 = \ell_2 = \ell$ and we subtract the second equation from the first one, we get

$$\frac{d^2(\varphi_1 - \varphi_2)}{dt^2} + \frac{g}{\ell}(\varphi_1 - \varphi_2) = 0$$

In this way we have eliminated the effect of the disturbing acceleration, a, and that is the fundamental principle of this method. In combining two pendulums, swinging in the same plane, we get a fictitious, undisturbed free pendulum with the "mathematical" length, ℓ, and with the phase angle $(\varphi_2 - \varphi_1)$.

1.6 If ℓ_1 and ℓ_2 would be exactly equal this effect would be completely eliminated, but since it is not quite so, we get a small disturbing term, which must be considered.

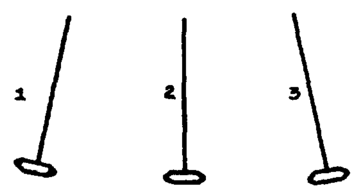

Fig. 1 Vening Meinesz uses three pendulums, swinging in the same plane. The middle pendulum 2 is immobile at the beginning while pendulums 1 and 3 have opposite phases. In combining the pendulums 1 and 2 as well as 2 and 3 we get two "fictitious" pendulums which are free from the horizontal acceleration of the submarine.

1.7 It is still better to use three pendulums of equal length, swinging in the same plane. If their phase angles are φ_1, φ_2 and φ_3,

we get two fictitious pendulums with the phase angles $(\varphi_1 - \varphi_2)$ and $(\varphi_3 - \varphi_2)$ and therefore a control. In the beginning of the measurements the middle pendulum (phase angle φ_2) is immobile and the others are in extreme opposite positions. After a little while the middle pendulums begin to swing too, because of the sway, although its swinging angle is small. (Fig. 1 and 2 show the principle of the Vening Meinesz three pendulum apparatus).

1.8 This instrument will be installed in a submarine, which dives for the measurements to a depth of 30 to 50 m. Since there are several other disturbing effects the apparatus and the measuring procedure is more complicated. In this connection it will be enough to mention that these disturbing effects can be considered so that the accuracy of the sea gravity measurements is of the order of 2 mgal.

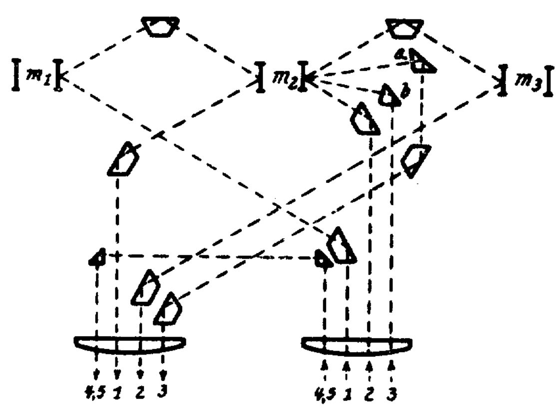

Fig. 2 shows the path of the light beams in the record box. The rays 1, 2 and 3 register the swinging angles $(\varphi_1 - \varphi_2)$ respectively $(\varphi_3 - \varphi_2)$ and φ_2. The prisms, a, and, b, are fastened to the additional pendulum which can swing in the swinging plane of the principal pendulums. The ray 4 registers the temperature of the air and the ray 5 the inclination of the swinging plane in respect to the vertical plane.

1.9 In order to get such accuracy we must register besides the swinging angles $(\varphi_1 - \varphi_2)$ and $(\varphi_3 - \varphi_2)$ also the swinging angle φ_2. in regards to an additional highly dampened pendulum swinging in a parallel plane to the swinging plane of the principal pendulums. This record is necessary because of the incomplete isochronism of the pendulums as well as for reducing the swinging angles to the infinite small angles. Another dampened pendulum which swings in the plane perpendicular to the swinging plane of the other pendulums gives us the possible inclination of the swinging plane of the principal pendulums.

1.10 A great deal has been written about the Browne's term, discovered in 1937 by B. C. Browne from the University of Cambridge, England. This is the effect for a few second order disturbances, caused by the wave movements of the ocean which for strong movements can rise to many mgals, in some cases even to 30 - 40 mgal. In general, however, it is much smaller, a few mgals only. The effect of Browne's term has been considered in most of the American and European gravity measurements at sea.

SECTION II

REDUCTION OF THE GRAVITY MEASUREMENTS AT SEA

2.1 As all gravity measurements, also the gravity measurements at sea have to be reduced to the sea level. The reductions in the case of ocean measurements are the following:

2.2 At first it has to be considered that gravity has been measured in a submarine about 30m below sea level so that the free air reduction with the opposite sign has to be employed to reduce gravity from the observation point in the submarine to sea level.

2.3 The attraction of the water layer between "station" and sea level has to be considered. Since this water layer is situated above the station, it diminishes the gravity by the same amount as it increases the gravity at sea level. In order to find the gravity of the sea level we have to add <u>twice</u> the effect of the water layer.

2.4 The reduction to sea level therefore is

$$-\frac{2g}{r}\,t + 2\cdot\frac{3}{2}\frac{\delta'}{\delta_m}\,\frac{g}{r}\,t = -\frac{2g}{r}\left(1 - \frac{3}{2}\frac{\delta'}{\delta_m}\right)t = -0.2225\ t\ \text{mgal}$$

where t is the depth of the "station" in meters, r the earth's radius of curvature, δ' the water density and δ_m the mean density of the earth. If we assume that $t = 30$ m, then this reduction is -6.7 mgal. Using this we get the gravity value at the sea surface. Since all masses in the oceans are situated below the sea surface, that is, below the

geoid level, the gravity values obtained in this way can be used for the determination of the earth shape.

2.5 Furthermore, the mass anomalies of the ocean waters have to be considered. Since the density of water (1,03) is lower than that of the earth crust (2,67) the observed gravity must be too small and we have to add the influence of mass on density, $\delta'' = 2{,}67 - 1{,}03 = 1{,}64$ to the observed gravity value. This reduction is similar to a Bouguer reduction and is given by

$$+ \frac{3}{2} \frac{\delta'}{\delta_m} \frac{g}{r} T = + 0{,}0688 \times t' \text{ mgal } (t' \text{in meter})$$

where $\delta'' = 1{,}64$ and t' the depth of the sea water at the observation point. If $t' = 4000$ m, then this reduction amounts to + 275 mgal.

2.6 If we add this "Bouguer reduction" to the observed gravity then the reduced gravity becomes much too large in comparison to gravity values on the continent at the same latitude. This indicates most clearly, that the mass anomalies of the oceans are isostatically compensated by the subterranean mass anomalies. For this reason gravity measurements at sea have to be reduced isostatically, which is quite simple, excepting ocean deeps and the areas close to steep coasts. Its amount will generally not be very different from the "Bouguer reduction", but its sign is negative.

2.7 We also have to consider the Eötvös-effect, which is brought about by the east-west velocity of the submarine. The east velocity of the submarine increases the centrifugal force of the vessel and this diminishes the observed gravity.

In order to determine this east or west velocity component and the centrifugal force caused by it, we must know the velocity and the course of the submarine and of the ocean streams. If ω is the angular east velocity of the earth, the centrifugal acceleration caused by it, c equals

$$c = \omega^2 \cdot r \quad \text{and} \quad dc = 2\omega \cdot r d\omega,$$

where r is the distance from the earth's axis.

Then

$$dg = -dc \cos \varphi = -2\omega \cos \varphi \cdot r d\omega$$

2.8 If the eastern linear velocity component of the ship relative to the earth equals v, then, instead of $r d\omega$ the value v has to be used and the change in gravity becomes

$$dg = -2\omega v \cos \varphi$$

If $\varphi = 0$ and $v = 20$ km/h = 555 cm/sec, then this so-called "Eötvös effect" is -81 mgal. Therefore, in order to get this effect on 1 mgal, one has to determine v with an accuracy of approximately 250 m/h. This can be difficult now and then because of the poor knowledge of ocean currents. Owing to this fact the error of the gravity anomalies at sea is greater--up to 5 mgal--than the gravity measurements themselves would presume.

SECTION III

GRAVITY MEASURING CRUISES AT SEA

According to my knowledge the following gravity measuring trips at sea have been carried out so far.

3.1 The gravity measuring trips of Vening Meinesz

1) In 1923 a gravity measuring trip from the Netherlands via the Mediterranean and Red Sea to the East Indies.

2) In 1925 a similar trip to the East Indies.

3) In 1927 a world-wide trip from the Netherlands via the Atlantic, Panama Canal, Hawaii and the Philippines to Java.

4) In 1928 a measuring trip in the West Indies and on the Caribbean Sea under invitation of the Agencies of the United States.

5) In 1929 to 1930 an extensive measuring trip in the waters of the East Indian Archipel; through these measurements Vening Meinesz, among other things, discovered the 8,000 km long belt of negative gravity anomalies beginning south west of Sumatra, surrounding Java and Celebes and continuing to the Philippines Deep.

6) In 1932 a measuring trip with the American scientists to the Island group of the West Indies.

7) In 1932 a measuring trip through the Atlantic as well as a round trip in the form of the figure eight around the Azores and Madeira.

8) In 1934-5 from the Netherlands via Madeira and Cap Verde Islands to Dakar, then to Pernambuco, South America, along the coast of South America to Buenos Aires, then across the Atlantic to Cape Town, then to Mauritius, to West Australia and lastly to Java. This trip, as long as the earth equator, took eight months and was very rugged because he, like Odysseus during his time, had to weather big storms.

9) In 1937 one trip from the Netherlands to the West Indies and back.

10) After World War II Vening Meinesz has carried out at least two gravity measuring trips back and forth from the Netherlands to the West Indies.

3.2 <u>The American Gravity Measuring Trips</u>

We have mentioned already the gravity measuring trips in 1928 and 1932 in which Vening Meinesz participated as an expert. In 1947 the Geophysical Laboratory of the Columbia University began under the direction of Maurice Ewing an extensive gravity measuring program at sea. This work has been supported by the Geological Society of America and the United States Navy. These measurements include, according to a letter which Prof. Ewing has kindly sent to me:

1) June-July 1947, 104 observations off the northeast coast of the United States.

2) Sept.-Oct. 1947, 86 stations off the west coast of South America.

3) Oct.-1947, 56 stations off the northeast coast of South America.

4) Feb. 1948, 180 stations in the waters off the Bahama Islands.

5) May-June 1948, 118 stations off the southeast coast of the United States.

6) Aug.-Dec. 1948, 260 stations, San Diego-Hawaii-Australia--Japan-Hawaii.

7) Dec. 48-Jan. 1949, 103 stations, Pearl Harbor-Australia-Guam.

8) Mar.-Apr. 1949, 72 stations, off the West Coast of Central America.

9) Jul.-Sept. 1949, 142 stations, off the West Coast of North America to Chukchi Sea.

10) Dec. 49-Apr. 1950, 155 stations, Hawaii-Japan-Philippines-Hawaii.

11) June-July 1950, 108 stations, Hawaii-Panama-New London.

12) Mar.-April 1951, 39 stations, New London-Mediterranean.

13) May 1951, 33 stations, Mediterranean-Norfolk.

14) July-Aug. 1951, 105 stations, San Diego-Hawaii-Japan.

15) Jan. 1952, 43 stations, off the Gulf of Maine.

3.3 Other Gravity Measuring Trips at Sea

1) In 1931 an Italian expedition in the Western Basin of the Mediterranean.

2) In 1936 a French expedition, also in the Western Part of the Mediterranean. (In both these gravity measuring trips Vening Meinesz participated as an expert.)

3) In 1930, 1933 two Russian gravity measuring trips in the Black Sea.

4) In 1934, 1935 two Japanese gravity measuring trips carrying out twelve profiles across the Nippon Trench east of Japan.

5) Several British gravity measuring trips in the waters surrounding the British Isles.

6) In 1950 a Spanish gravity measuring trip from Spain to the Canary Isles.

7) In 1951 a British expedition in the eastern basin of the Mediterranean.

3.4 I think that this list is not complete but it contains in any case the bulk of the gravity measurements at sea carried out by now. It shows also that the interest in these measurements is universal. The outstanding individuals involved in these studies are, besides Vening Meinesz, the inventor of this method, Professors Maurice Ewing and Lamar Worzel.

SECTION IV

OBJECTIONS TO THE OCEANIC GRAVITY SURVEY

4.1 In spite of the obvious success the gravity measurements at sea have had and of the universal significance of them for the geodetic and geophysical applications of gravity anomalies I have been told about some objections to the gravity measurements at sea in general. As far as I know, these objections have not been published. But as I have heard, certain individuals speak of them on several occasions and they may have been mentioned in some interagency circulars in the United States. Therefore, it might be advisable to discuss them briefly.

4.2 First objection: Gravity measurements at sea go very slowly, in fact so slowly, that one submarine can carry out only seven gravity measurements a month.

The truth is: As I have mentioned already, Vening Meinesz made in 1934-35 a gravity measuring trip from Holland to Dakar, South America, Cape Town, Australia and Java during eight months. He measured gravity at least at 200 stations, or an average of 25 stations a month despite very bad weather conditions and in spite of the fact that the speed of his submarine was not very high. According to him, a submarine expedition can measure on the average three gravity points a day at an interval of 80 km. According to Dr. Worzel the Columbia group made last year a gravity measuring trip

from New London to Gibraltar in 11 days, measuring gravity at 33 stations. It came back from Gibraltar to New London in 11 days, measuring gravity at 35 stations. Another trip from San Diego to Tokyo with 105 gravity measurements took only 25 days. The experience obtained thereby has shown that three to four gravity measurements can be carried out a day if the distance between the points is not more than 100 km. If we say that the capacity of a submarine expedition, under the mentioned conditions, is 100 stations a month we at least do not promise too much. If the interval of stations is less, e.g. 30 km about twice as many points can be measured.

4.3 Second Objection: To carry out the additional gravity measurements at sea which are needed for a geodetic application of the world-wide gravity field would require 20 years if only one submarine is available.

The truth is: All needed additional measurements for the general gravity anomaly map of the world can be easily carried out in two years by one submarine expedition. A fairly good anomaly map can already be obtained on the basis of the new gravity measurements taken by a single submarine expedition during one year.

4.4 Third Objection: The gravity measurements at sea are erroneous. Why? Because the gravity anomalies at sea are systematically positive.

The truth is: The gravity anomalies at sea are in fact more positive than negative. Of 844 gravity anomalies measured by Vening Meinesz at sea 471 anomalies are positive and only 373 anomalies are negative. (F.A. Vening Meinesz, Gravity Expeditions at Sea, 1923-1938, Vol. IV).

The gravity anomalies are in large areas of the oceans positive, but there are also extensive areas where they are negative. The oceans seem not to be very different from the continents. As we know, in large parts of Europe the gravity anomalies are systematically positive and e.g. in India in large areas they are negative. Nobody however, has claimed, by now that because gravity anomalies, e.g. in Europe are systematically positive all European gravity measurements are strongly erroneous.

If we claim that the gravity measurements at sea are erroneous because positive gravity anomalies have been obtained it is quite similar to saying that because the thermometer reading last December was more than 60° one day in Columbus, the thermometers of Columbus are erroneous.

The gravity anomalies are on large areas systematically positive or negative because there exist deep seated disturbing layers in the earth interior which bring them about.

4.5 Fourth objection: The accuracy of the gravity measurements at sea is very low, because of some error sources which have not been considered.

The truth is: According to Vening Meinesz and Worzel the mean error of these measurements is about 3-5 mgal, and still smaller if the speed of the ocean streams which has an influence on the gravity measurements is known. A good evidence for the accuracy of the gravity measurements at sea is the fact that in the East Coast Area of the United States the gravity anomaly terms of the Ocean area agree--according to Worzel--completely with the gravity anomaly curves of the near-lying flat land. No systematical difference between the gravity anomalies on inland and at sea had been found.

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